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SIMULATION AND ANALYSIS OF PERMANENT MAGNET SYNCHRONOUS GENERATOR FOR RENEWABLE ENERGY UTILIZATION

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ABSTRACT

This paper deals with the simulation of dynamic model of permanent magnet synchronous generator (PMSG) in D-Q axes of the rotor rotating reference frame. The iron core losses and stray load losses of the machine are taken into account. The iron core losses are represented by iron core resistance connected in parallel with magnetizing inductance and then reflected into the stator side as a voltage drop to prevent increasing the number of differential equations in the model. The modified equivalent circuit can deal with all machine parameters without losing the accuracy of generator performance calculations. The modified equivalent circuit can be used as an efficient tool for analysis, design, and vector control algorithm of this type of generator, especially in renewable energy utilization. The model is executed by Matlab Simulink and very good results are obtained and compared with the results of the experimental model to display the validity and accuracy of the proposed dynamic model.

Key words: PMSG, rotating reference frame, dynamic modeling, equivalent Circuit, iron core loss.

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1. INTRODUCTION

The main function of an electrical generator in renewable energy systems is to convert the rotational torque from wind or hydropower turbine as the prime mover into electrical power to feed the isolated load or the grid. Different kinds of generators are being used with hydro and wind turbines. The common type of AC generators that are candidates in micro-hydro and wind turbine systems are squirrel-cage induction generators and permanent magnet synchronous generators (PMSG).

Due to its advantages, recently, the PMSG is used in wind power systems. Its usefulness over the other kinds of generators are :

- Due to the absence of brushes, rotor windings, and slip-rings, this type of generator has high reliability.
- There is no additional excitation power supply due to the permanent magnet.
- There is no rotor copper loss due to no rotor winding.
- Lower maintenance, higher capacity, and higher massive/weight ratio.
- This type of generator can be made with a large amount of magnetic poles and the turbine rotor coupled directly to the generator shaft.
- Due to the low generator speed, there is no need for a gearbox.

Because of the many benefits of this type of generator in renewable energy conversion, all researchers [1-23] mentioned in this work have taken up this topic to analyze and represent this type of generator employing a dynamic model. But all those who studied the mathematical model of the generator type (PMSG), used an incomplete dynamical model, as the iron core losses, stray load loss, and magnetizing saturation effect are not taken in the dynamic model. Also, there are no results in their analysis indicating the validity of the mathematical model. These types of machine losses cannot be omitted when performance and efficiency determination is required. Also, in all those dynamic models the excitation capacitance, which is linked in series with each stator phase of the generator is not considered. The excitation capacitance can be linked in series with machine terminals to obtain maximum output power from the generator at synchronous speed and resonance conditions.

In the new and comprehensive dynamic model used in this research, the effect of machine stray load losses and iron core losses were included. The magnetizing saturation effect is also considered in the model due to this type of generator is operating in a non-linear saturation region at full load. The machine equivalent circuit is modified for comprehensive analysis without increasing the number of system differential equations or losing the accuracy of the performance calculations by converting the iron core resistance into a voltage drop on the stator circuit. The capacitor was also inserted in series with the machine terminals to get the higher output power from the generator at synchronous speed and resonance conditions.

This work is structured in four sections; the first section is dealt with the introduction, the second section is dealt with the detailed dynamic model of the PMSG. The third section deals with the results and discussion while the last section deals with the conclusion.

2. DYNAMIC MODELING OF PMSG

The permanent magnet synchronous generator (PMSG) in figure (1) can generate electrical energy if its rotor rotating at a suitable speed by wind or hydro turbine as an external prime mover. The generator terminal voltage is build-up due to the permanent magnet fixed on the rotor with a suitable number of magnetic poles. Capacitors are linked in series with each phase to obtain higher output power from the generator at resonance condition.

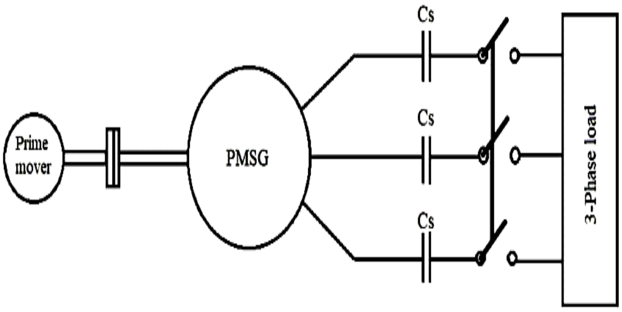
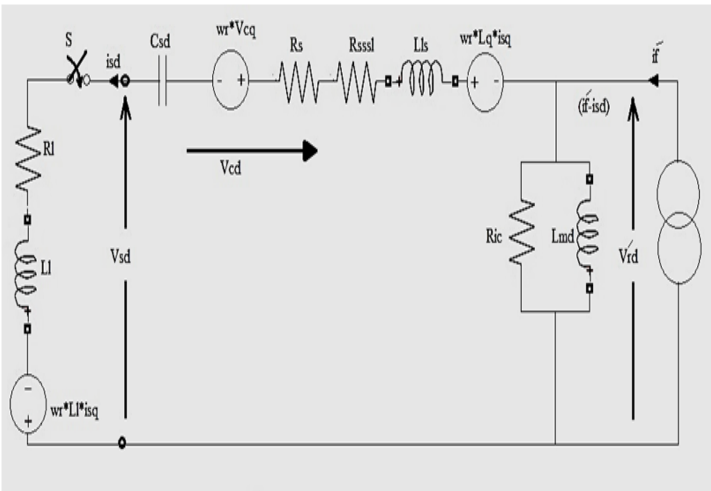
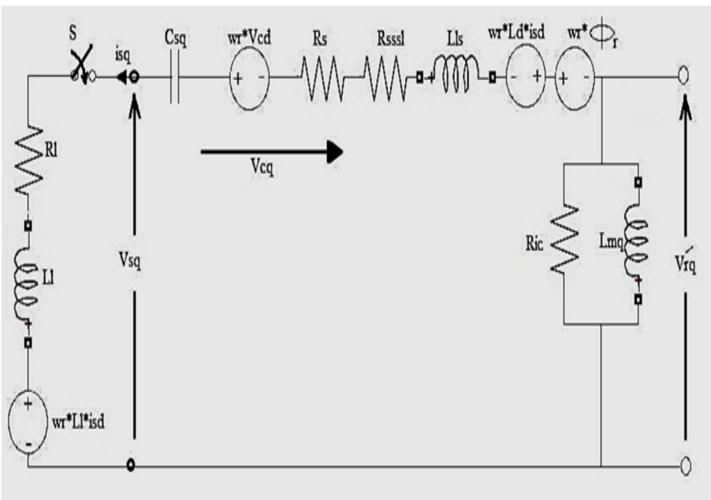


Figure 1 PMSG driven by a prime-mover

Figure (2) exhibits the per-phase equivalent circuit of the PMSG in D-Q axes rotating frame with inductive load and series capacitance, taking the effect of machine iron core losses and stray losses. The iron core losses and stray losses are represented by equivalent iron core resistance (R_{ic}) connected in parallel with the magnetizing inductance, and stray load loss resistance ($R_{sss\ell}$) connected in series with the stator circuit.



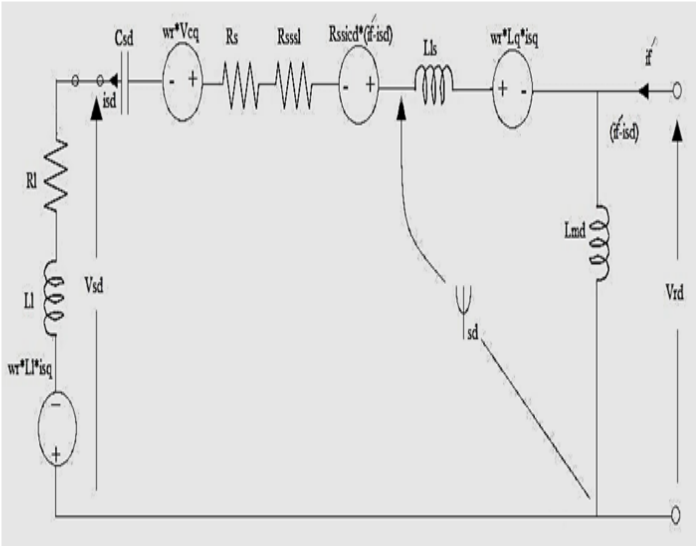
D-axes



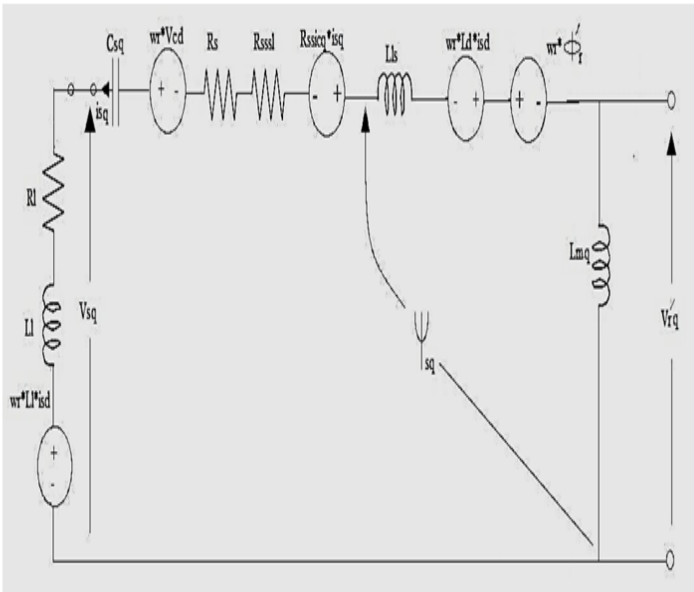
Q-axes

Figure 2 D-Q axes equivalent circuit of PMSG

Figure (3) shows the modified equivalent circuit of the PMSG. In this circuit, the parallel branch of the iron core resistance (R_{ic}) is replaced by series resistance and then reflected as a voltage drop in the stator circuit [24]. The magnetizing inductance in D-Q axes (L_{Md} and L_{Mq}) are modified.



D-axes



Q-axes

Figure 3 Modified equivalent circuit of PMSG in D-Q axes rotor rotating frame

The stator series stray load resistance ($R_{sss\ell}$), the modified iron core resistance (R_{ssicd} and R_{ssicq}) and the modified magnetizing inductance (L_{md} and L_{mq}) in the D-Q axes model can be obtained as [25, 26]:

$$R_{sss\ell} = (w_r * L_{\ell s})^2 * R_s/[R_s^2 + (w_r * L_{\ell s})^2] \quad (1)$$

$$R_{ssicd} = R_{ic} * w_r * L_{Md}/[R_{ic}^2 + (w_r * L_{Md})^2] \quad (2)$$

$$R_{ssicq} = R_{ic} * w_r * L_{Mq}/\left[R_{ic}^2 + (w_r * L_{Mq})^2\right] \quad (3)$$

$$L_{md} = L_{Md} * R_{ic}^2/[R_{ic}^2 + (w_r * L_{Md})^2] \quad (4)$$

$$L_{mq} = L_{Mq} * R_{ic}^2/[R_{ic}^2 + (w_r * L_{Mq})^2] \quad (5)$$

Where R_s : the stator phase resistance.

w_r : rotor speed in electrical radian/second.

L_{Md} : D-axis magnetizing inductance/phase.

L_{Mq} : Q-axis magnetizing inductance/ phase.

R_{ic}: iron core resistance obtained from the no-load test as:

$$R_{ic}=V_o/[P_{nl} - I_o^2*(R_s+R_{sss\ell})]$$

V_o & I_o: no-load phase voltage and current when the machine is driven as a motor.

P_{nl}: no-load power per phase when the machine is driven as a motor.

The D-Q axes series capacitance (C_{sd} and C_{sq}) in each phase must satisfy the following condition at resonance and synchronous speed to obtain maximum generator output power:

$$C_{sd} = 1 /[w_r^2 * (L_{Md} + L_{\ell s} + L_\ell)] \quad (6)$$

$$C_{sq} = 1 /[w_r^2 * (L_{Mq} + L_{\ell s} + L_\ell)] \quad (7)$$

Where L_ℓ : the load inductance per phase. In case of round or cylindrical rotor machine:

$$L_{Md} = L_{Mq} = L_M \quad (8)$$

$$C_{sd} = C_{sq} = C_s \quad (9)$$

The voltage in D-Q axes of the stator and rotor of PMSG with series capacitance and inductive load derived from the modified circuit of figure (3) as:

$$v_{sd} = -v_{cd} - R_s * i_{sd} - R_{sss\ell} * i_{sd} - R_{ssicd} * (\acute{\imath}_f - i_{sd}) + w_r * L_q * i_{sq} - L_d * \frac{di_{sd}}{dt} \quad (10)$$

$$v_{sq} = -v_{cq} - R_s * i_{sq} - R_{sss\ell} * i_{sq} - R_{ssicd} * i_{sq} - w_r * L_d * i_{sd} + w_r . \acute{\phi}_r - L_q * \frac{di_{sq}}{dt} \quad (11)$$

$$\acute{v}_{rd} = w_r . \acute{\phi}_r - i_{sd} * L_{md} \quad (12)$$

$$\acute{v}_{rq} = -w_r * L_{mq} * i_{sq} \quad (13)$$

$$v_{cd} = \int \left(\frac{i_{sd}}{C_{sd}} + w_r * v_{cq}\right) dt + V_{cdo} \quad (14)$$

$$v_{cq} = \int \left(\frac{i_{sq}}{C_{sq}} + w_r * v_{cd}\right) dt + V_{cqo} \quad (15)$$

$$\Psi_{sd} = -L_{\ell s} * i_{sd} + (\acute{\imath}_f - i_{sd}) * L_{md} = -L_d * i_{sd} + \acute{\phi}_r \quad (16)$$

$$\Psi_{sq} = -(L_{\ell s} + L_{mq}) * i_{sq} = -L_q * i_{sq} \quad (17)$$

Where v_{sd} , v_{sq} , i_{sd} and i_{sq} , stator phase voltages and currents in D-Q axes respectively.

$\acute{\phi}_r$ is the permanent magnetic flux per phase referred to the stator circuit?

$\acute{\imath}_f$ is the field current generated in the rotor due to the permanent magnet referred to the stator circuit?

$$\acute{\imath}_f = \acute{\phi}_r / L_{md} \quad (18)$$

$L_d = (L_{\ell s} + L_{md})$ is the stator d-axis self-inductance.

$L_q = (L_{\ell s} + L_{mq})$ is the stator q-axis self-inductance.

For round rotor machine $L_d = L_q = L_s$

The stator (r.m.s) phase voltage can be obtained as:

$$V_{ph} = [v_{sd}^2 + v_{sq}^2]^{\frac{1}{2}}/\sqrt{2} \quad (19)$$

In the case of resistive-inductive load the components of phase voltage $\left(v_{sd} and\ v_{sq}\right)$ can be calculated as:

$$v_{sd} = R_\ell * i_{sd} + L_\ell * \frac{di_{sd}}{dt} - w_r * L_\ell * i_{sq} \tag{20}$$

$$v_{sq} = R_\ell * i_{sq} + L_\ell * \frac{di_{sq}}{dt} + w_r * L_\ell * i_{sd} \tag{21}$$

Where R_ℓ and L_ℓ , load resistance and inductance per phase.

The stator phase currents (i_{sd} & i_{sq}) and their derivatives in first-order differential equations can be obtained from equations (10) and (11) as:

$$\frac{di_{sd}}{dt} = (1/L_d) * \left[-v_{sd} - v_{cd} - (R_s + R_{sss\ell}) * i_{sd} - R_{ssicd} * \left(\acute{i}_f - i_{sd}\right) + w_r * L_q * i_{sq}\right] \tag{22}$$

$$\frac{di_{sq}}{dt} = \left(1/L_q\right) * \left[-v_{sq} - v_{cq} - \left(R_s + R_{sss\ell} + R_{ssicq}\right) * i_{sq} - w_r * L_d * i_{sd} + w_r * \acute{\phi}_r\right] \tag{23}$$

The electromagnetic torque generated by PMSG can be obtained as:

$$T_e = \left(\frac{3}{2}\right).\left(P_p\right) * \left[\acute{\phi}_r * i_{sq} - \left(L_d - L_q\right) * i_{sd} * i_{sq}\right] \tag{24}$$

In the case of a round rotor or cylindrical machine, the torque becomes:

$$T_e = \left(\frac{3}{2}\right).\left(P_p\right) * \acute{\phi}_r * i_{sq} \tag{25}$$

Where P_p magnetic pole pairs.

The generator mechanical speed (w_m) in radian/second can be obtained as [1]:

$$\frac{dw_m}{dt} = \frac{1}{J}\left(T_m - T_e - K_f * w_m\right) \tag{26}$$

Where J total moment of inertia in Kg.m^2.

T_m prime mover torque in N.m.

K_f friction coefficient (N. m/(rad./sec.)).

The rotor speed in electrical radian/second can be obtained as:

$$w_r = P_p * w_m \tag{27}$$

The generator input power can be obtained as:

$$P_{in} = T_e * w_m \tag{28}$$

The generator output power delivered to the load can be calculated as:

$$P_{out} = P_{in} - 3 * I_{ph}^2 * (R_s + R_{sss\ell}) \tag{29}$$

Where I_{ph} load current per phase and can be obtained as:

$$I_{ph} = \left[i_{sd}^2 + i_{sq}^2\right]^{\frac{1}{2}}/\sqrt{2} \tag{30}$$

Alternatively, the load active and reactive power can be obtained as:

$$P_\ell = \left(\frac{3}{2}\right) * \left(v_{sd} * i_{sd} + v_{sq} * i_{sq}\right) \tag{31}$$

$$Q_\ell = \left(\frac{3}{2}\right) * \left(v_{sq} * i_{sd} - v_{sd} * i_{sq}\right) \tag{32}$$

The load power factor can be calculated as :

$$P.F. = P_\ell/[P_\ell^2 + Q_\ell^2]^{\frac{1}{2}} \tag{33}$$

The generator efficiency can be calculated as:

$$\eta\% = \frac{P_\ell}{(P_{in}+P_{rot})} * 100 \tag{34}$$

Where P_{rot} is the total rotational (mechanical) losses for generator and prime mover.

The PMSG usually has higher efficiency than the other types of generators due to the fixed magnet for the generation of rotor flux.

3. DYNAMIC SIMULATION RESULTS

The dynamic simulation model of PMSG is developed in Matlab Simulink.

The PMSG is driven experimentally at synchronous speed by a DC motor as a prime mover and the capacitors are connected in series with generator terminals to obtain maximum output power from the generator at resonance conditions. The parameters of the PMSG are given as :

PMSG Parameters: 3-phase, round rotor, 230 V per phase; 2 kW with the following parameters :

$R_{ic} = 300\Omega$; $R_s = 3\ \Omega$; $R_{sss\ell} =$ $R_\ell = 20\ \Omega$; $L_\ell = 0.1\ mH$;

$L_{\ell s} = 10\ mH$; $\acute{\phi}_r = 0.11\ wb\ per\ phase$; $P_p = 2$; $K_f = 0.003\ \ N.m/(rad./sec.)$

$J_g = 0.03\ kg\ .m^2$. The dynamic magnetizing inductance which is found from the no-load test in terms of magnetizing current (I_m), represented by a polynomial curve-fitting technique as :

$$L_{Md} = L_{Mq} = 0.04765 * \ I_m^5 - 0.3129 * \ I_m^4 + 1.18 * \ I_m^3 - 2.57 * \ I_m^2 + 2.636 * \ I_m + 0.15$$

Figure (4-a.b) shows the Matlab and practical results for the starting-up condition of the generator terminal voltage. Figure (5-a.b) shows the Matlab and practical results of the steady-state phase voltage of the PMSG. From these figures, there is a very close agreement between the simulation and practical results, which indicates the validity of the proposed dynamic simulation model. Figures (6-7) show the simulation results of PMSG electromagnetic generated torque and output active power per phase of the generator. There is very close agreement between the theoretical and practical results due to all machine parameters, especially iron core loss, stray load loss, and the saturation effect are considered in the comprehensive dynamical model of the PMSG.

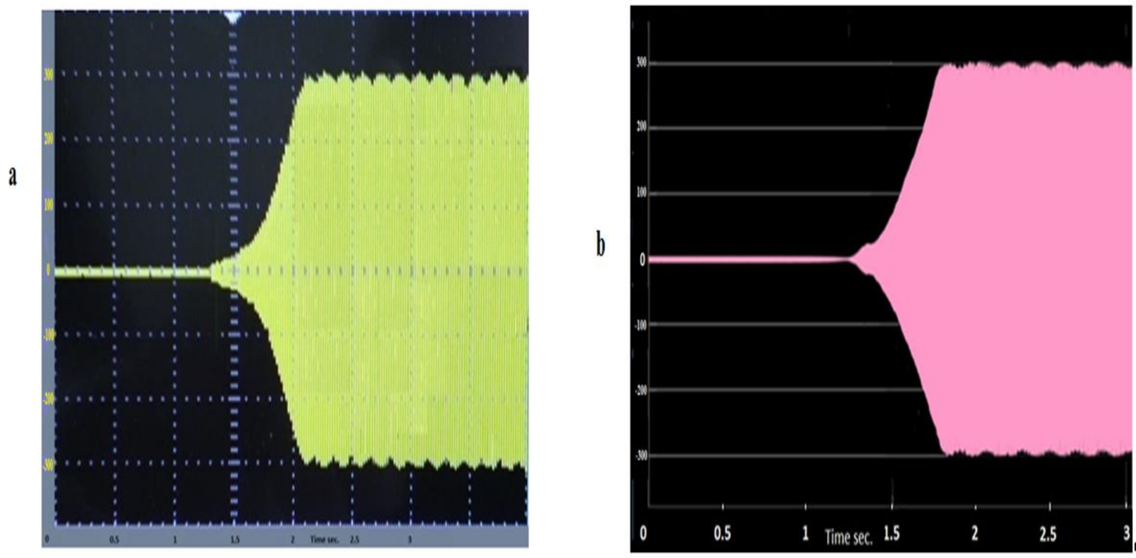


Figure 4-a,b Experimental result (a) and simulation result (b) of starting–up generator terminal voltage at the no-load condition.

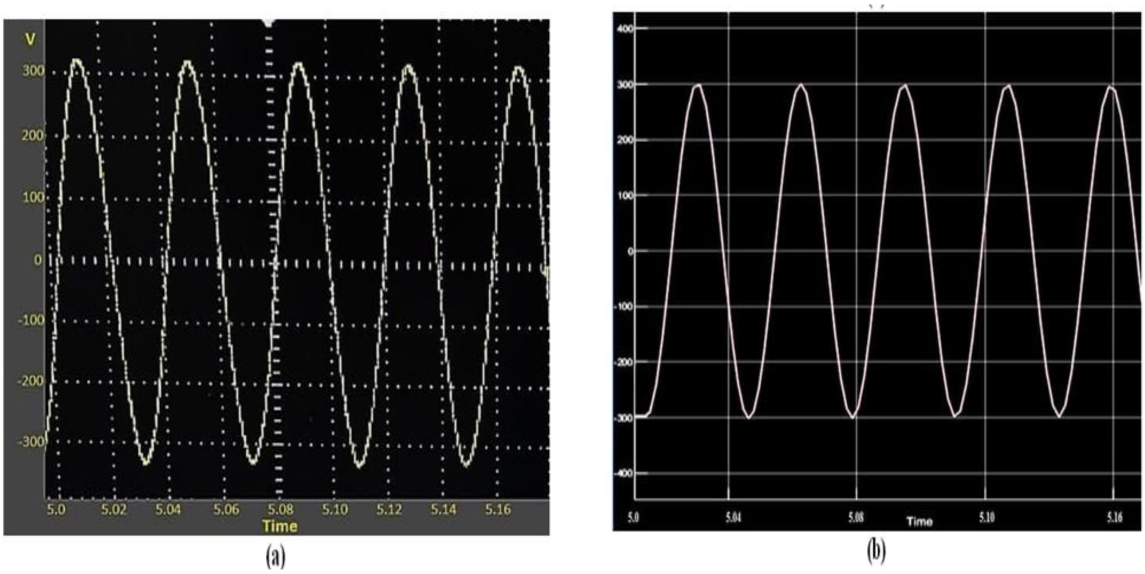


Figure 5-a,b Experimental result (a) and simulation result (b) of the steady-state generator phase voltage

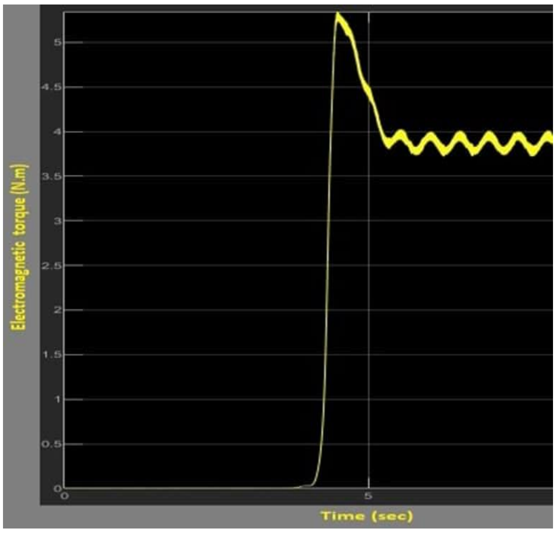


Figure 6 Simulation result of electromagnetic torque

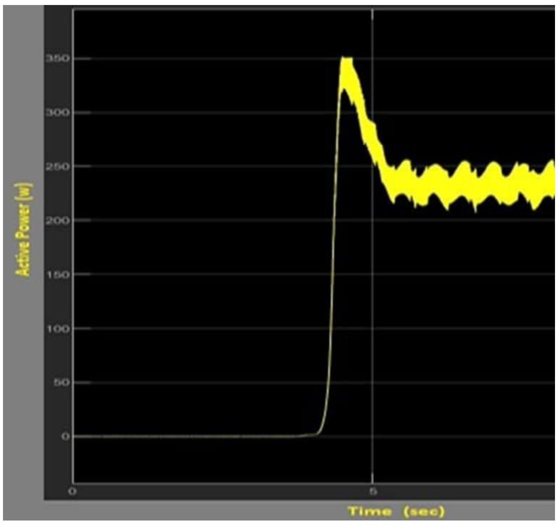


Figure 7 Simulation result of active power per phase

4. CONCLUSION

A comprehensive dynamic model of PMSG is considered in detail in this paper taking the effect of iron core losses and stray load losses of the machine into account without increasing the number of differential equations of the model. The effect of iron core loss is represented by a resistance reflected in the stator circuit as a voltage drop. The stray load loss is represented by a series resistance connected in the stator circuit. The equivalent circuit of PMSG is modified to deal with all machine parameters without losing the accuracy of the machine performance determination. A series capacitance is connected in each generator terminal to obtain maximum output power from the generator when operates at synchronous speed and resonance conditions.

CONFLICT OF INTEREST

The author declares no potential conflict of interest in this article's work.

REFERENCES

[1] B. Wu, Y. Lang, N. Zargan and S. Kouro, " Power conversion and control of wind energy system", *IEEE Book, IEEE press, published by John Wiley and Sons*, 2011.

[2] G. El-Saady, El-Nobi A. Ibrahim, H. Ziedan and M. M. Soliman, " Analysis of wind turbine driven permanent magnet synchronous generator under different loading conditions ", *Journal of Innovative Systems Design and Engineering*, Vol. 4, No. 14, Pp 97-111, 2013.

[3] A. K. Singh, R. Krisham and Y. Sood," Modeling control of grid-connected variable speed PMSG based wind energy system ", *Conference on Advances in Communication and control system (CAC2S)*, Pp 134-139, 2013.

[4] V. Behjat and M. Hamrahi, " Dynamic modeling and performance evaluation of axial flux PMSG based wind turbine system with MPPT control ", *Ain Shams Engineering Journal, Ain Shams University*, Vol. 5, Pp 1157-1166, 2014.

[5] D.C. Aliprantis, S.A. Papathanassious, M.P. Papadopoulos and A.G. Kladas, " Modeling and control of variable-speed wind turbine equipped with permanent magnet synchronous generator", *IEEE International Conference on Advances in Green Energy (ICAGE ' 14)*, December 2014.

[6] El M. Youness, Z. Othmane, D. Aziz and El G. Abdelaziz," Dynamic modeling and control of a wind turbine with MPPT control connected to the grid by using PMSG ", *ATSIP*, *Fez, Morocco, May* 22-24, 2017.

[7] A. Rolan, A. Luna, G. Vazquez, and G. Azevedo, " Modeling of a variable speed wind turbine with a permanent magnet synchronous generator ", *IEEE International Symposium on Industrial Electronics (ISIE2009), Seoul Olympic Parktel, Seoul, Korea*, July 5-8, 2009.

[8] S. Li, T. A. Haskew, and L. Xu, " Conventional and novel control designs for direct-driven PMSG wind turbines ", *Journal of Electrical Power Systems Research*, Vol. 80, Pp 328-338, 2010.

[9] J. C. Dai, Y.P. Hu, D.S. Liu and J. Wei, " Modeling and analysis of direct driven permanent magnet synchronous generator wind turbine based on wind rotor neural network model ", *Journal of Power and Energy, Proceedings of the Institution of Mechanical Engineers, Part-A*, Vol. 226, Pp 62-72, October 21, 2011.

[10] Z. Fan, " Mathematical modeling of grid-connected fixed-pitch variable-speed permanent magnet synchronous generators wind turbines", *M.Sc. Thesis, University of Central Lancashire*, June 2012.

[11] K. Parikh, A. Maheshwari and V. Agarwal, " Modeling, simulation and performance analysis of AC-DC-AC PWM converters based wind energy conversion systems ", *International Journal of Recent Technology and Engineering (IJRTE)*, Vol. 2, Issue-4, Pp 1-7. September 2013.

[12] E. Mahersi, A. Khedher, and M.F. Mimouni, " The wind energy conversion system using PMSG controlled by vector control and SMC strategies ", *International Journal of Renewable Energy Research*, Vol. 3, No. 1, Pp 41-50, 2013.

[13] Y. Errami, M. Ouassaid and M. Maaroufi, " Control of a PMSG based wind energy generation system for power maximization and grid fault conditions ", *Energy Procedia, Published by Elsevier*, Vol. 42, Pp 220-229, 2013.

[14] C.N. Wang, W.C. Lin, and X.K. Le, " Modeling of a PMSG wind turbine with autonomous control ", *Journal of Mathematical Problems in Engineering*, Vol. 2014, Article ID 856173, 9 pages, 2014.

[15] S. Sharma, A. Shrivastav, H. Rawat and V. Warudkar, " Modeling and control of permanent magnet synchronous generator connected to grid driven by wind turbine using a fast simulator and SVPMW Technique ", *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, Vol. 9, Issue 4, Pp 61-71, July-August, 2014.

[16] Syafaruddin, Z. Muslimin, F.R. Said, A.T. ananda and S. Latief, " Modeling and simulation of wind power with permanent magnet synchronous generator (PMSG) ", *ICIC International Express Letters*, Vol. 10, No. 9, Pp 2121-2127, September 2016.

[17] H. Slah, D. Mehdi and S. Lassaad, " Advanced control of a PMSG wind turbine ", *International Journal of Modern Nonlinear Theory and Application*, Vol. 5, Pp 1-10, 2016.

[18] A. Jain, S. Shankar, and V. Vanitha, " Power generation using permanent magnet synchronous generator (PMSG) based variable speed wind energy conversion system (WECS): An overview", *Journal of Green Engineering*, Vol. 7, Issue 4, Pp 477-504, October 2017.

[19] E. Mohammadi, R. Fadaeinedjad and H.R. Naji, " Design, electromechanical simulation, and control of a variable speed stall-regulated PMSG-based wind turbine ", *International Journal of Green Energy, Taylor and Francis Group*, DOI: 10.1080/15435075. 2019. 1641714, 24 July 2019.

[20] Y. Belkhier, A. Achour, N. Ullah and R.N. Shaw, " Modified passivity-based current controller design of a permanent magnet synchronous generator for the wind conversion system ", *International Journal of Modeling and Simulation*, *Taylor and Francis Group*, DOI: 10.1080/02286203. 1858226, November 2020.

[21] J. Baran and A. Jaderko, " An MPPT control of a PMSG-based WECS with disturbance compensation and wind speed estimation ", *Journal of Energies*, Vol. 13, No. 6344, Pp 1-20, DOI: 10.3390 | en13236344, 2020.

[22] K. E. Okedu and H. Barghash, " Enhancing the transient state performance of permanent magnet synchronous generator based variable speed wind turbines using power converters excitation parameters ", *Journal of Frontiers in Energy Research*, Vol. 9, Article ID 655051, April 2021.

[23] A. A. Ghany et al.," Novel switching frequency FCS-MPC of PMSG for grid-connected wind energy conversion system with coordinated low voltage ride through ", *Electronics*, Vol. 10, No. 492, Pp 1-19, 2021.

[24] B.A. Nasir," An accurate iron core loss model in the equivalent circuit of induction machines ", *Journal of Energy, Hindawi Publisher*, Vol. 2020, Article ID 7613737, Pp 1-10, 2020.

[25] B.A. Nasir, " Dynamic modeling of wound-rotor slip-ring induction generator with switched-excitation capacitance and chopper resistance across bridge rectifier in the rotor circuit," *Turkish Journal of Electrical Engineering and Computer Sciences*, Vol. 29, No. 3, Pp, 2021.

[26] B.A. Nasir, " Modeling of stray losses in the equivalent circuit of induction machines ", *AIP Conference Proceedings*, Vol. 2307, Pp 1-10, 15 December 2020.